

# Modeling RF Systems

**Andrea Borgioli**

**Tom Cwik**

[borgioli@canyonlands.jpl.nasa.gov](mailto:borgioli@canyonlands.jpl.nasa.gov)

[cwik@jpl.nasa.gov](mailto:cwik@jpl.nasa.gov)

California Institute of Technology



High Performance Computing Group  
*Imaging and Spectrometry Systems Technology Section*



# Intent

- To study the feasibility of modeling **Quasi-Optical Systems** with software packages based on an **optical** approach



# Motivation

- Different software packages exist. Some are based on a pure electromagnetic approach and some on an optical approach.



- Understanding the differences between these methods is needed for their appropriate use.



# Plan

- A comparison between a scalar diffraction theory and a full vector diffraction theory when used for modeling electrically large systems (such as telescopes, reflector antennas...)



- A better understanding of the applicability of different software tools



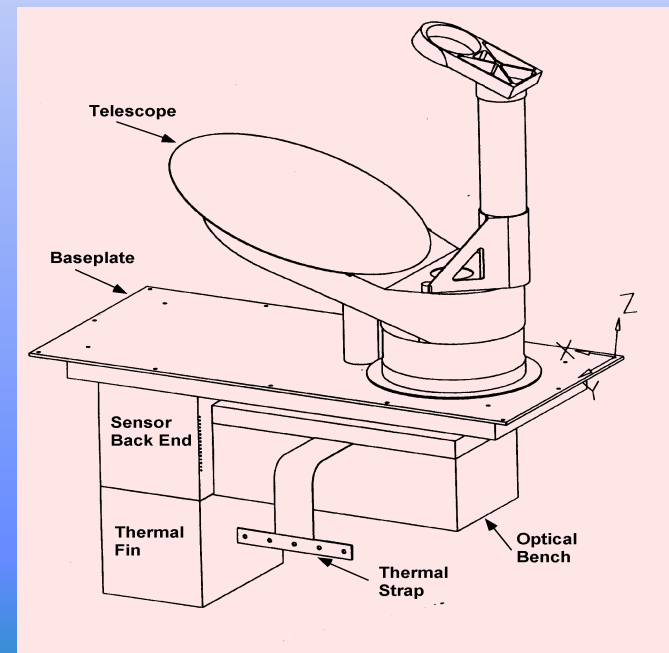
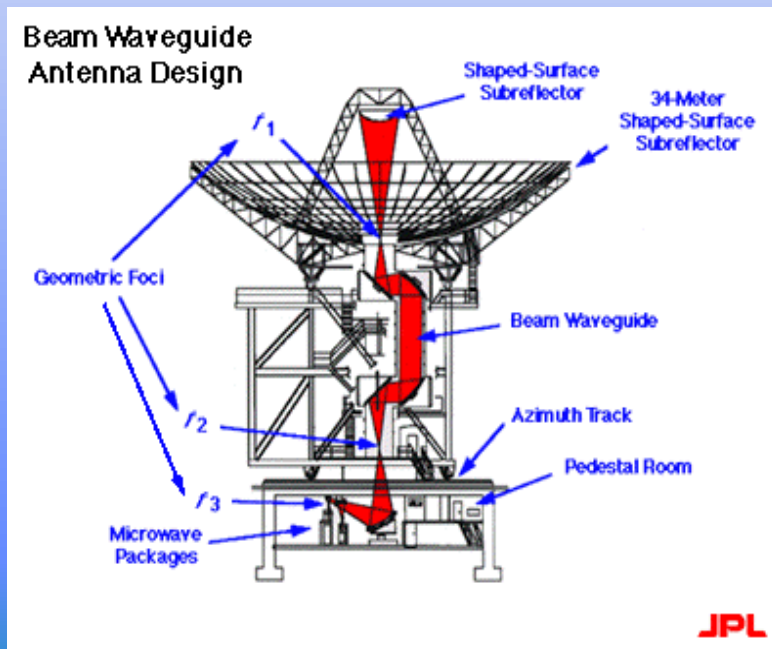
# Overview

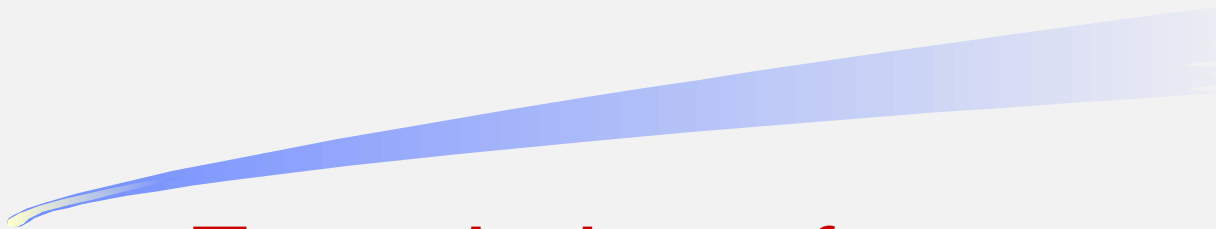
- Basic description
  - Full vector theory (Physical Optics)
  - Scalar theory (Fourier Optics)
  - Mathematical differences
- Examples and Results
  - POPO (Physical Optics)
  - MACOS (Fourier Optics)
- Conclusions

# Test systems

(Part of the) Deep Space  
Network antenna  
X-band (8.45 GHz)  
 $D/\lambda \sim 100$

(Microwave Instrument for the  
Rosetta Orbiter)  
MIRO Telescope  
240/560 GHz  
 $D/\lambda \sim 250/600$





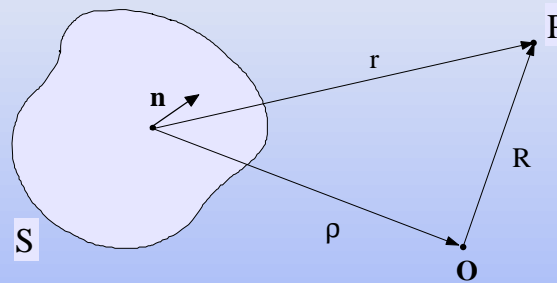
# Foundation of **vector** diffraction theory

Always start from Maxwell's equations:

$$\begin{aligned}\nabla \times \mathbf{E} &= -\mu \frac{\partial \mathbf{H}}{\partial t} & , & \quad \nabla \cdot \epsilon \mathbf{E} = 0 \\ \nabla \times \mathbf{H} &= \epsilon \frac{\partial \mathbf{E}}{\partial t} & , & \quad \nabla \cdot \mu \mathbf{H} = 0\end{aligned}$$



# Foundation of **vector** diffraction theory



$$\mathbf{E}(\mathbf{P}) = \frac{1}{4\pi} \int_S \{ (\mathbf{n} \times \mathbf{E}) \times \nabla \psi - j\omega\mu_o \psi (\mathbf{n} \times \mathbf{H}) + \frac{1}{j\omega\epsilon_o} [(\mathbf{n} \times \mathbf{H}) \cdot \nabla] \nabla \psi \} dS$$

$$\mathbf{H}(\mathbf{P}) = \frac{1}{4\pi} \int_S \{ (\mathbf{n} \times \mathbf{H}) \times \nabla \psi + j\omega\epsilon_o \psi (\mathbf{n} \times \mathbf{E}) - \frac{1}{j\omega\mu_o} [(\mathbf{n} \times \mathbf{E}) \cdot \nabla] \nabla \psi \} dS$$

**‘Vector diffraction integrals’**

# Foundation of **vector** diffraction theory

In terms of equivalent surface distributions

$$\mathbf{E}(\mathbf{P}) = \frac{1}{4\pi} \int_S \left\{ -\mathbf{M}_s \times \nabla \psi - j\omega\mu_o \psi \mathbf{J}_s + \frac{1}{j\omega\epsilon_o} [\mathbf{J}_s \cdot \nabla] \nabla \psi \right\} dS$$

$$\mathbf{H}(\mathbf{P}) = \frac{1}{4\pi} \int_S \left\{ \mathbf{J}_s \times \nabla \psi + j\omega\epsilon_o \psi \mathbf{M}_s - \frac{1}{j\omega\mu_o} [\mathbf{M}_s \cdot \nabla] \nabla \psi \right\} dS$$

# Foundation of **vector** diffraction theory

- The vector diffraction integrals are often applied to a metallic reflecting surface (reflector).

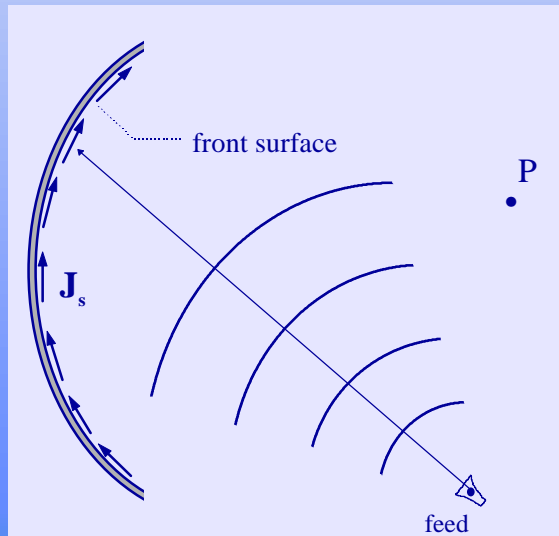
$$\Rightarrow \begin{aligned} \mathbf{E}(\mathbf{P}) &= \frac{1}{4\pi} \int_S \left\{ -j\omega\mu_o\psi\mathbf{J}_s + \frac{1}{j\omega\epsilon_o} [\mathbf{J}_s \cdot \nabla] \nabla\psi \right\} dS \\ \mathbf{H}(\mathbf{P}) &= \frac{1}{4\pi} \int_S \{ \mathbf{J}_s \times \nabla\psi \} dS \end{aligned}$$

- Evaluation of it requires the solution of an **integral equation**, since the induced surface-current distribution in the integral is unknown

# Foundation of **vector** diffraction theory

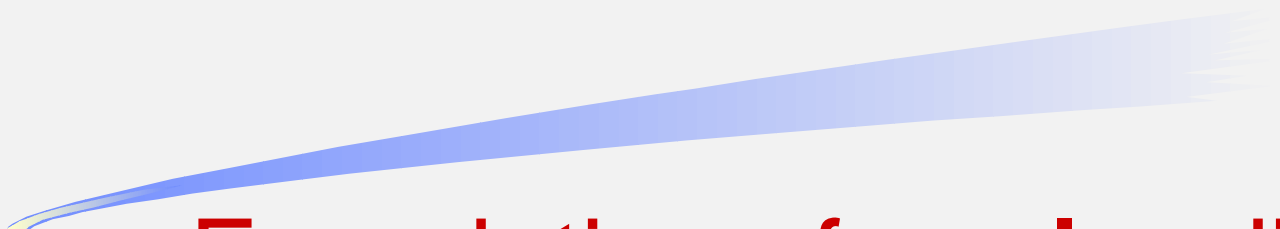
- An approximations of the currents is needed

## Physical Optics approximation:



$$\mathbf{J}_s = 2 (\mathbf{n} \times \mathbf{H}_{\text{inc}}) \quad \text{on front surface}$$

$$\mathbf{J}_s = 0 \quad \text{elsewhere}$$



# Foundation of **scalar** diffraction theory

Maxwell's equations

+

approximations

(medium: linear, isotropic,  
homogeneous and nondispersive)

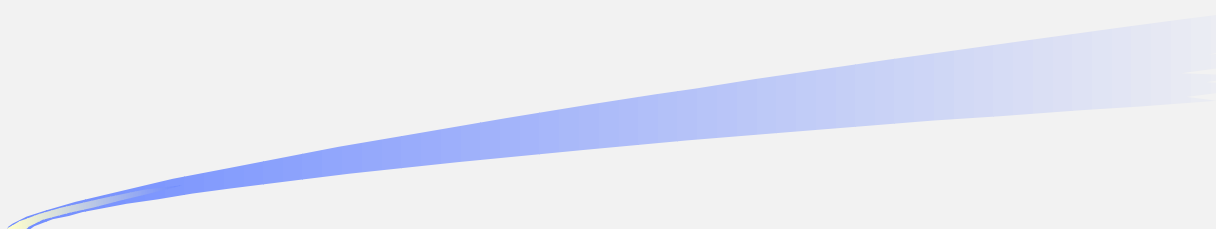


# Foundation of **scalar** diffraction theory

$$U(P) = \frac{1}{4p} \iint_S \left( \frac{\mathbf{y}}{\mathbf{n}} U - \mathbf{y} \frac{\mathbf{U}}{\mathbf{n}} \right) ds$$

**‘Scalar** diffraction integral’

- Fresnel/Fraunhofer formulas allow diffraction pattern calculations to be reduced to relatively simple expressions

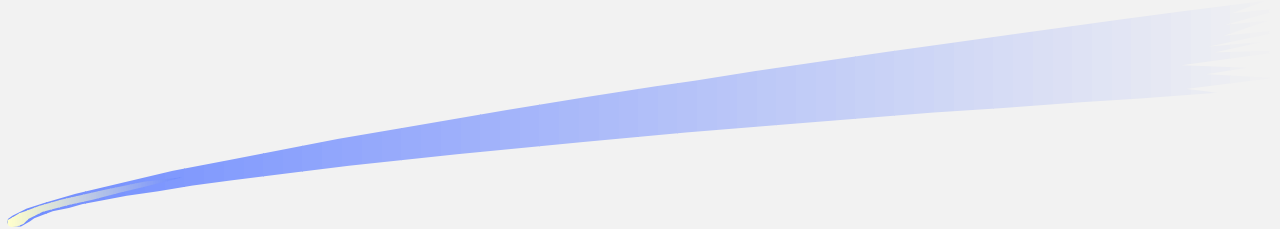


# Foundation of **scalar** diffraction theory

- The **Fresnel** approximation (~ near field): the spherical wavefronts are replaced by parabolic wavefronts

$$U(x, y) = (...) F \left\{ U(\epsilon, \eta) e^{j \frac{k}{2Z} (\epsilon^2 + \eta^2)} \right\} \bigg|_{\substack{f_x = x/\lambda z \\ f_y = y/\lambda z}}$$

F = Fourier Transform



# Foundation of **scalar** diffraction theory

- The **Fraunhofer** approximation (far field): the spherical wavefronts are replaced by flat wavefronts

$$U(x, y) = (...) F \left\{ U(\epsilon, \eta) \right\} \Big|_{\substack{f_x = x/\lambda z \\ f_y = y/\lambda z}}$$

F = Fourier Transform



## Are They Equivalent ?

- The scalar formulation is not generally valid for an open surface (vector integrals are not always equivalent to scalar integrals)



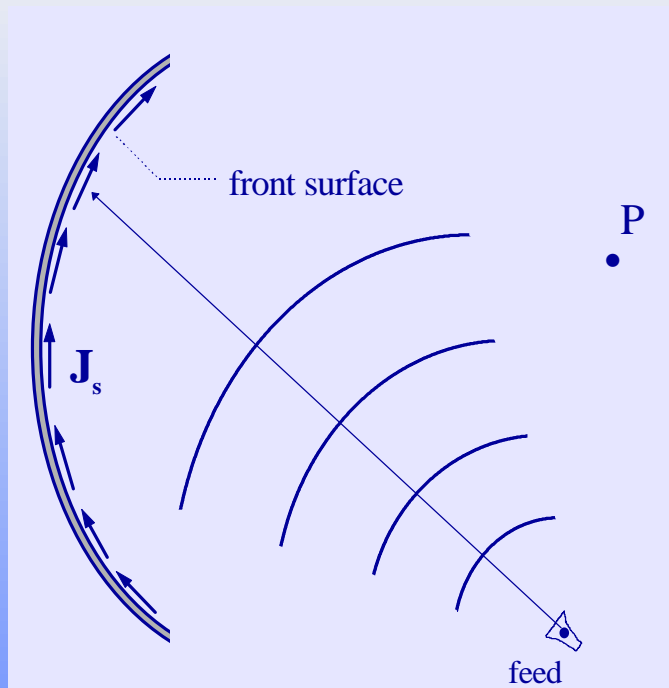
Optical approach

$\neq$

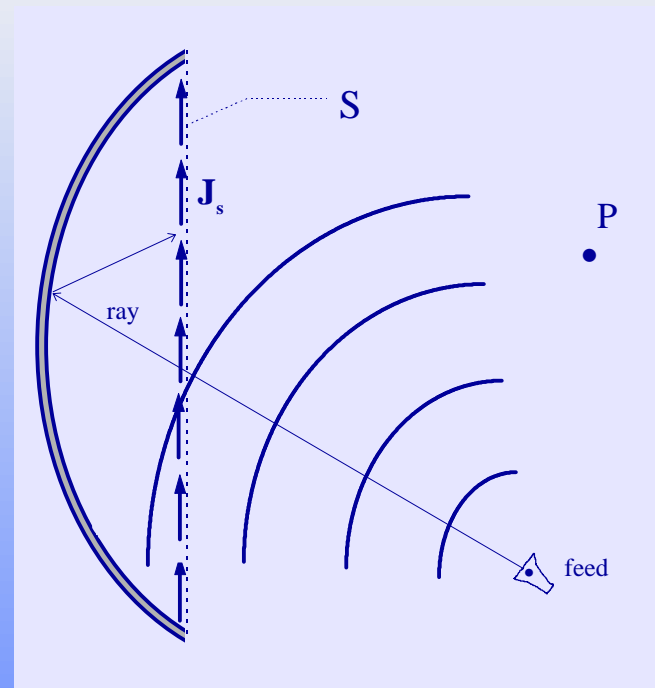
Full Electromagnetic approach

# Interpretation

Physical Optics



Fresnel/Fraunhofer formula



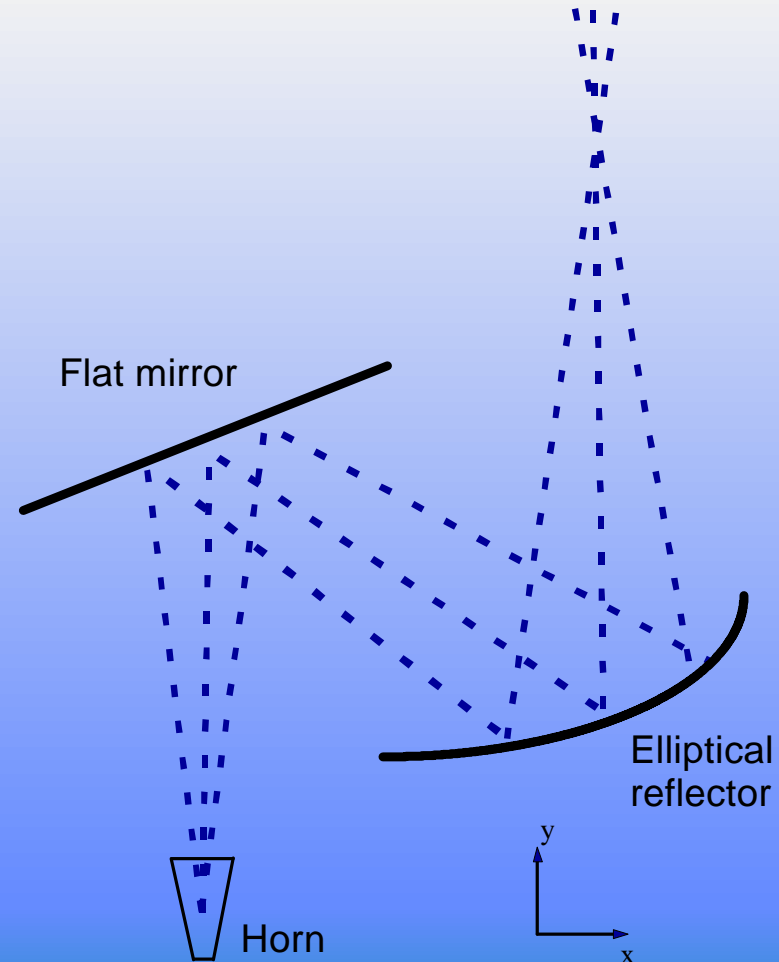
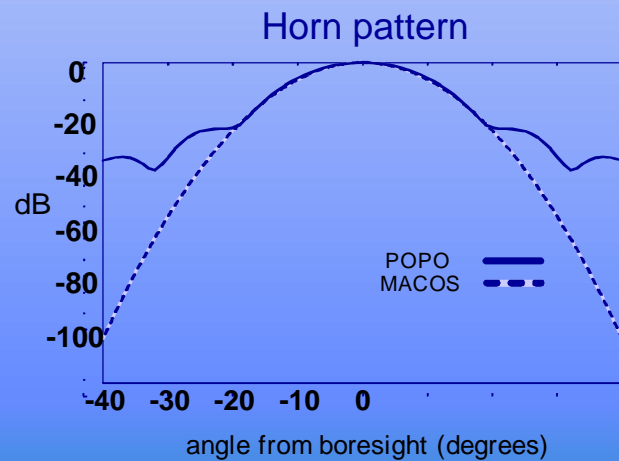
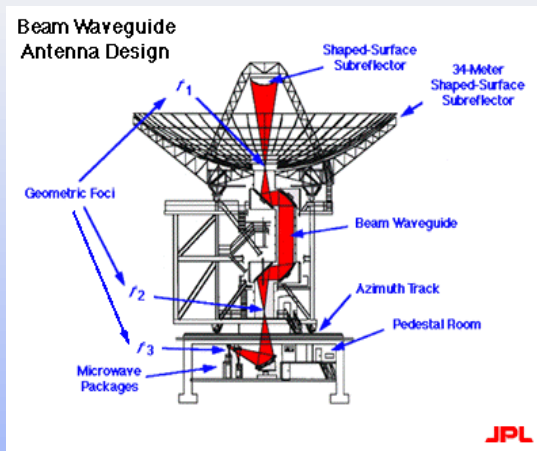
- Axially directed component of the currents are neglected
- Error is small on the optical axis, provided the angle of observation is small



# Test Codes

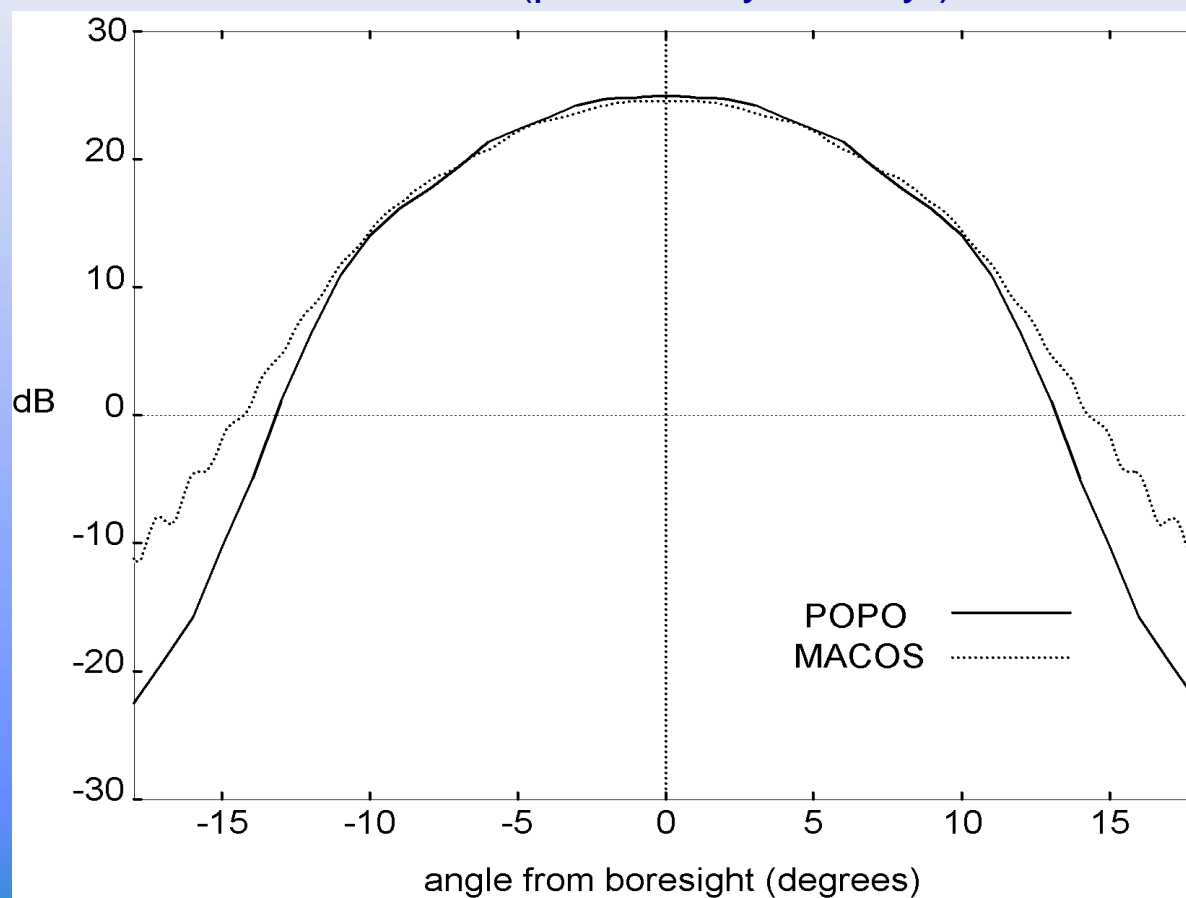
- **POPO** ('Physical Optics-Physical Optics')
  - based on a full electromagnetic theory
  - very accurate (our 'true' solution)
- **MACOS** ('Modeling and Analysing for Controlled Optical Systems')
  - based on Fourier Optics
  - successfully used for modelling optical systems

# Test system: DSN subsystem



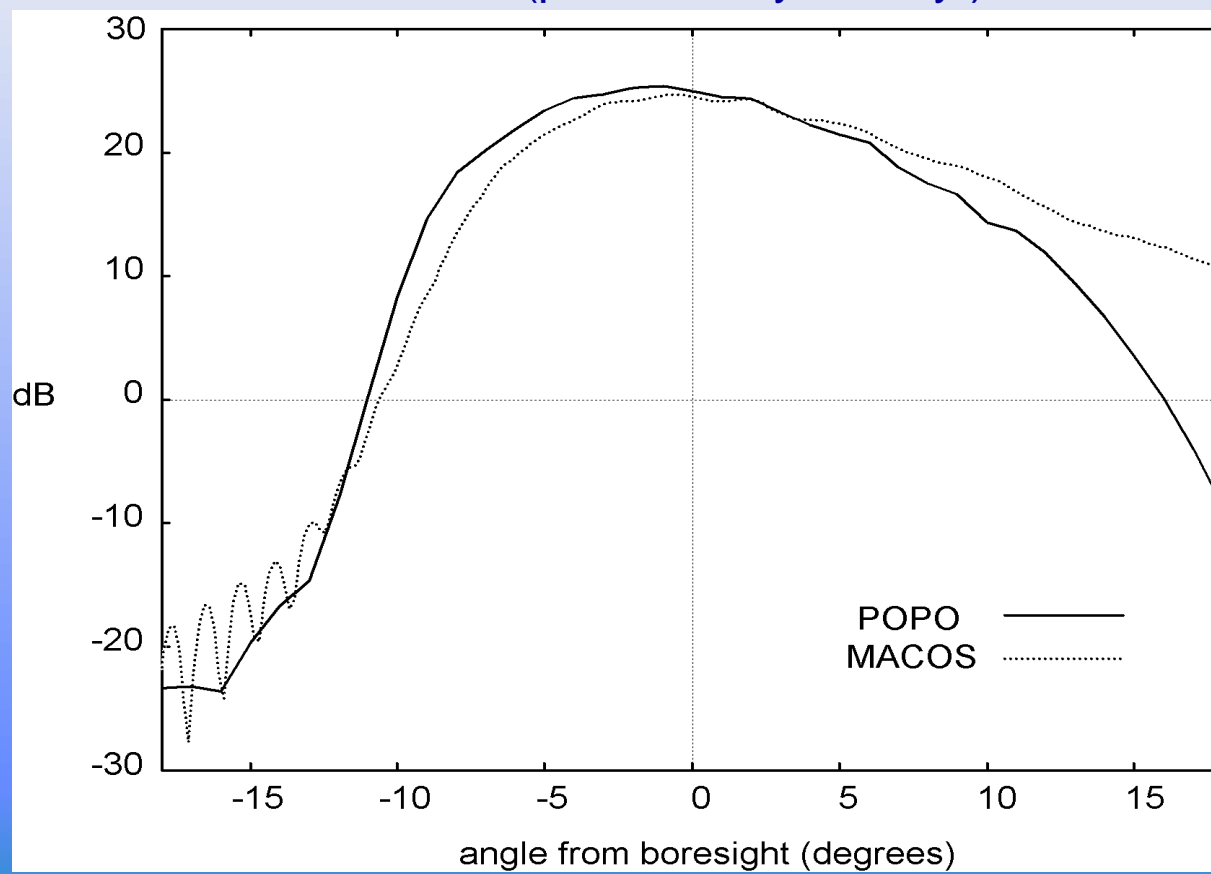
# Results

Far field pattern  
on XY (plane of symmetry)



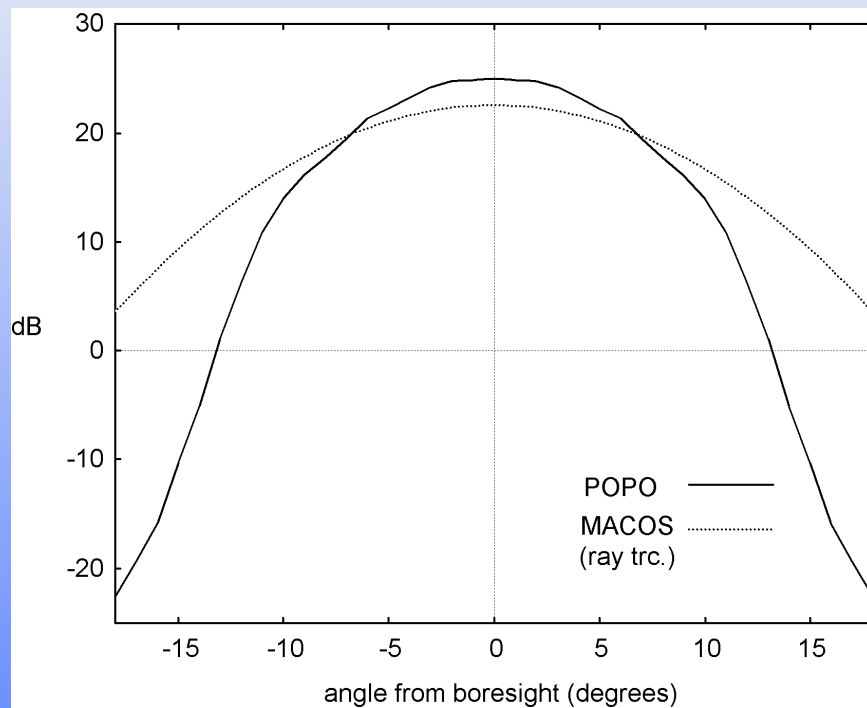
# Results

Far field pattern  
on YZ (plane of asymmetry)

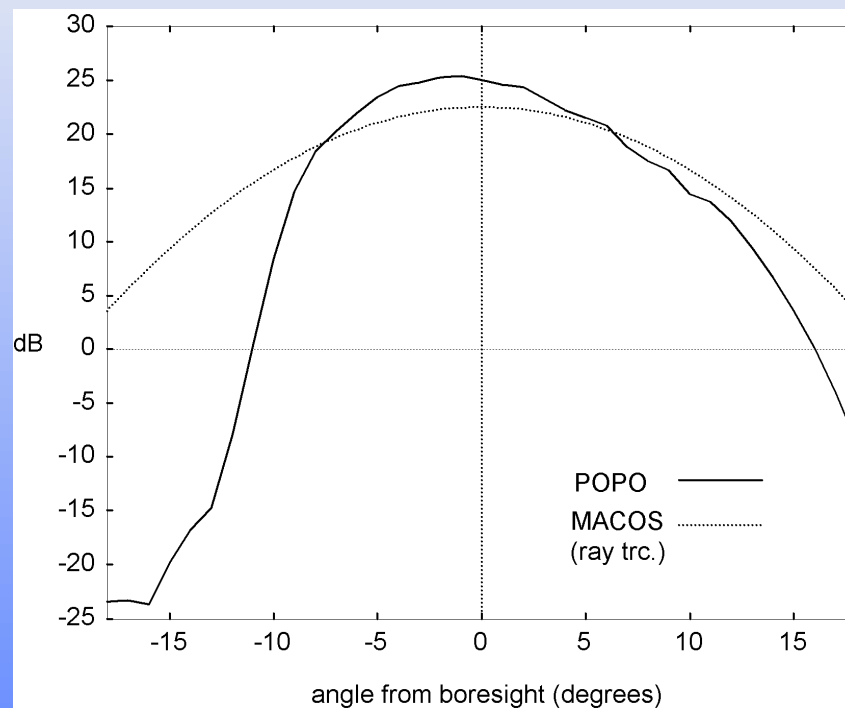


# Results

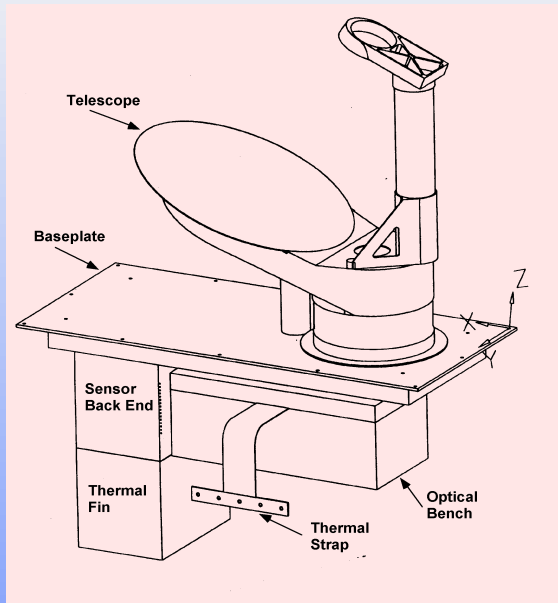
Ray tracing only  
on XY (plane of symmetry )



Ray tracing only  
on YZ (plane of asymmetry )

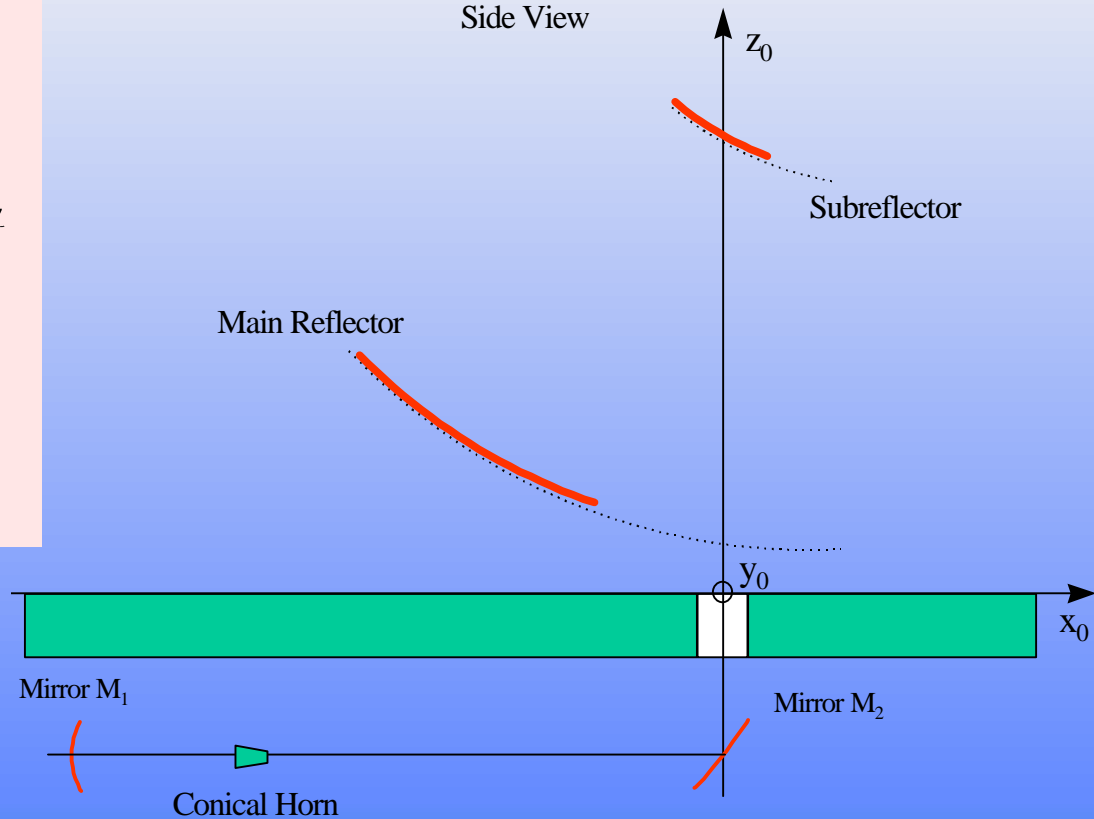


# Test system: MIRO telescope



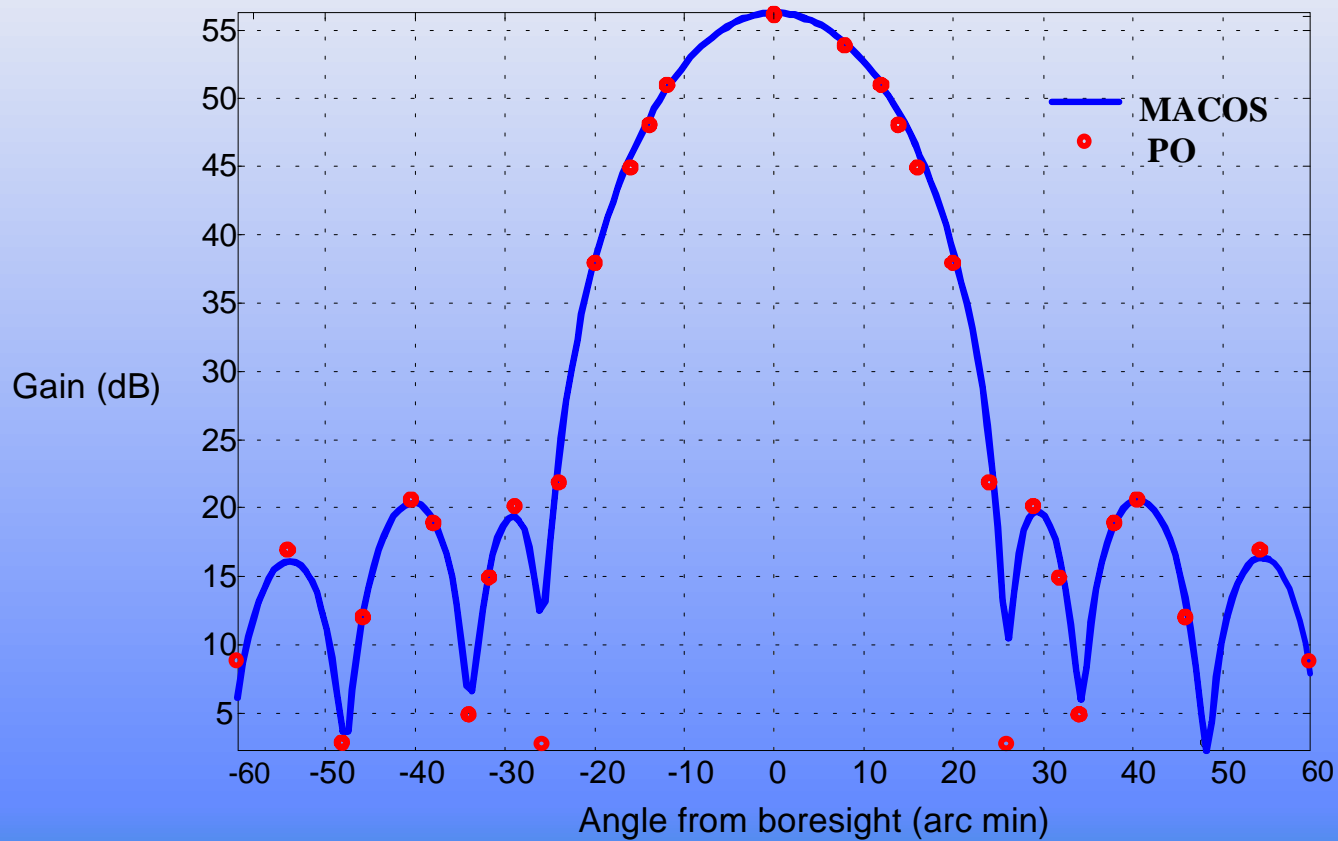
freq. = 240 GHz

Miro Telescope Configuration  
Side View



# Results

Far field pattern of main reflector at 240 GHz



# Computational tradeoff

## POPO

(radiation integral  
over the surface)



**computationally  
very expensive**



## MACOS

(Fast Fourier  
Transform)



**computationally  
inexpensive**



# Conclusions

- Optics-based software packages applied to electrically large systems may not provide accurate representations for the fields in regions of interest, but since they are computationally advantageous they can be a useful support in early design phases of RF systems.